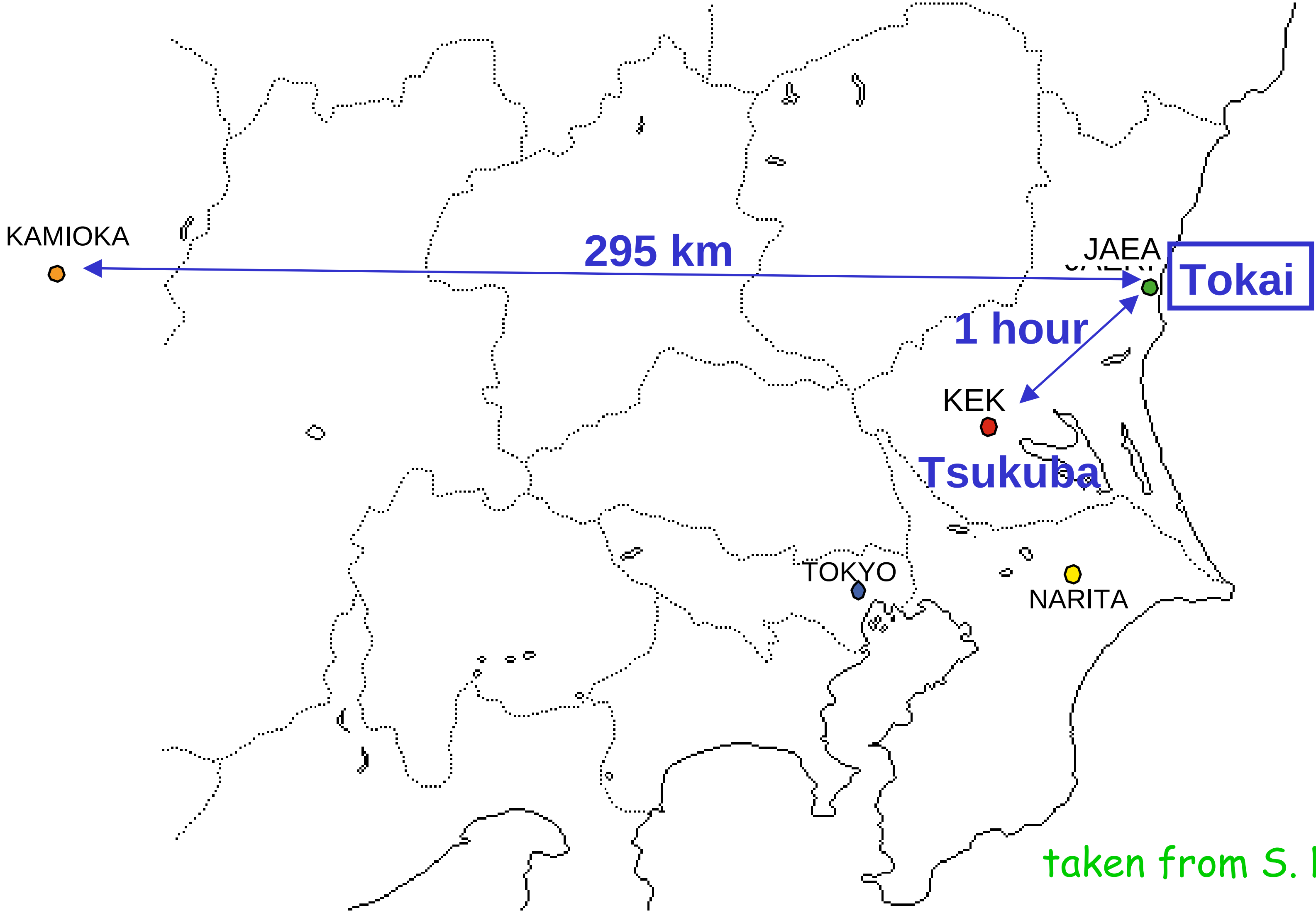
Hard Scattering and Spin Asymmetries at J-PARC

Marco Stratmann

J-PARC Japan Proton Accelerator Research Complex but before I start ...

... what is the J-PARC project ??

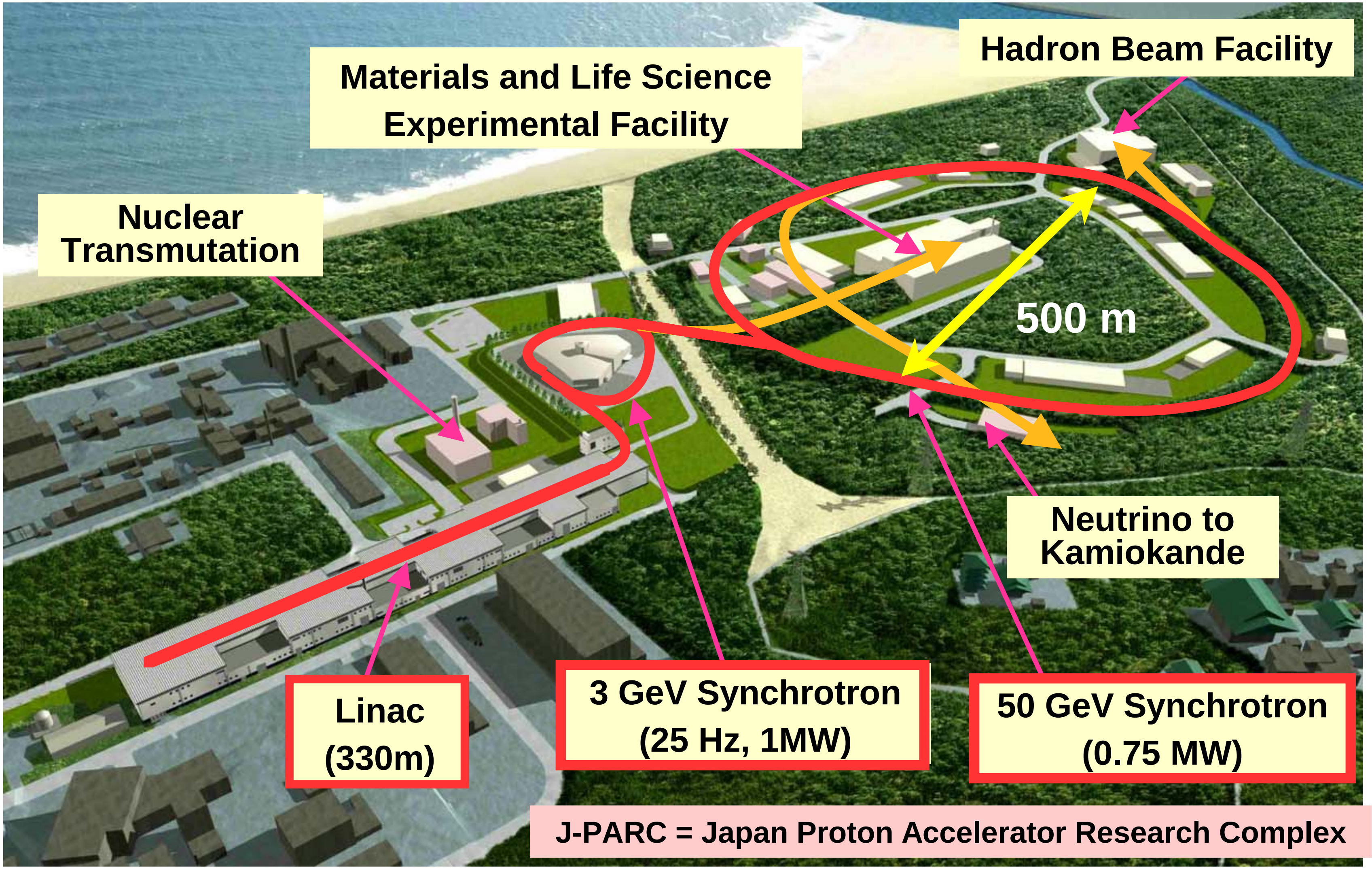
Location of J-PARC at Tokai



taken from S. Nagamiya

J-PARC Facility

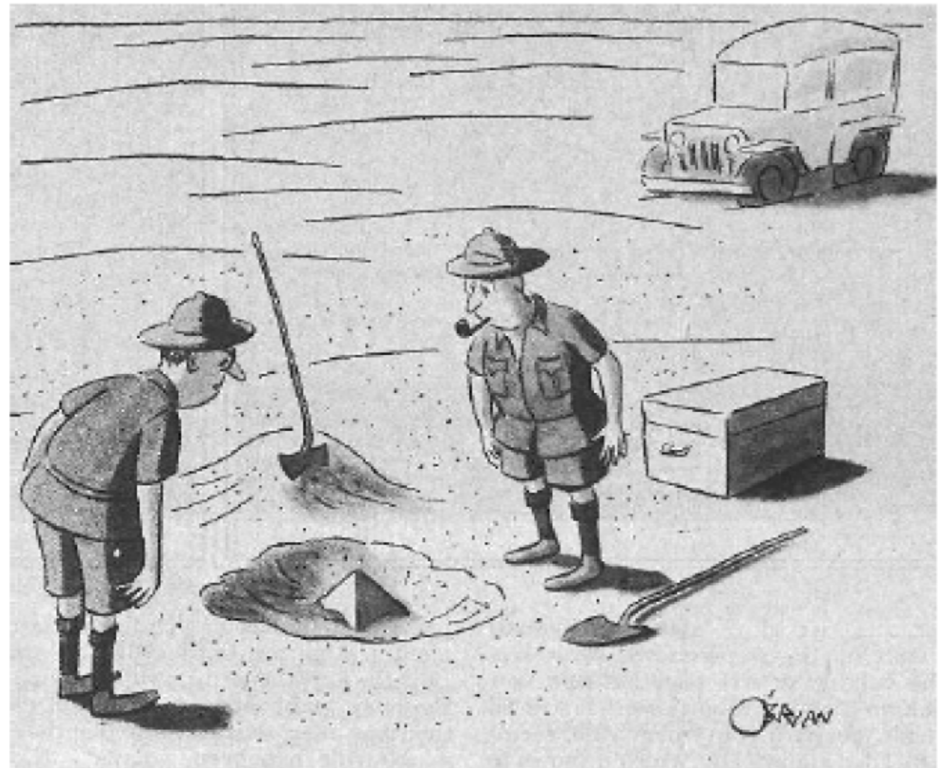
Joint Project between KEK and JAEA



taken from S. Nagamiya

Ground Breaking Ceremony

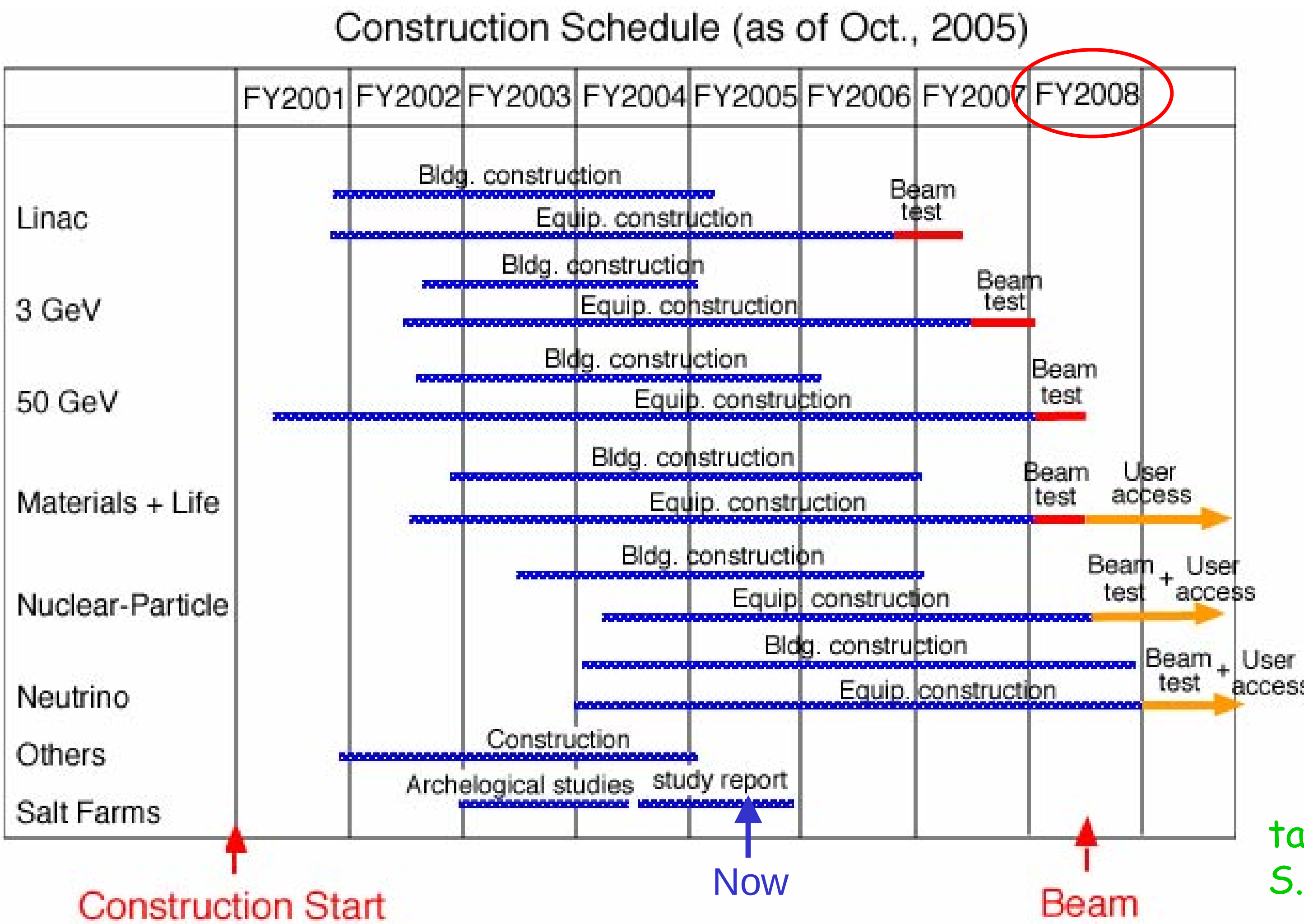
June, 2002



"This could be the discovery of the century. Depending, of course, on how far down it goes."

taken from S. Nagamiya

Schedule Proposed by Construction Group

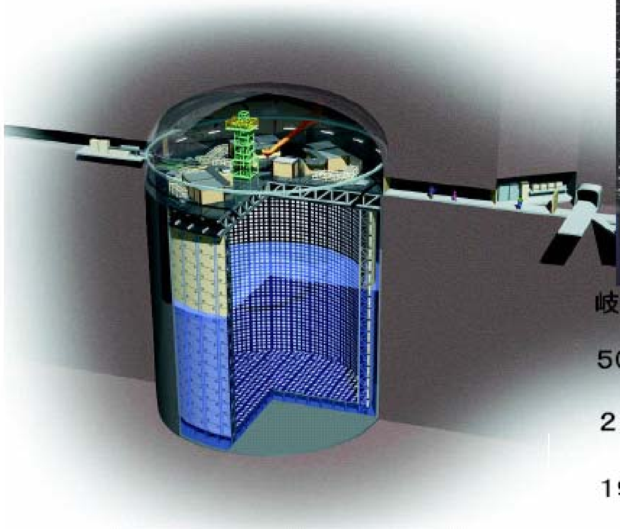


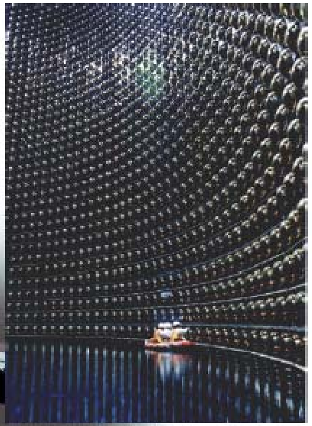
taken from S. Nagamiya

295 km
West

Super Kamiokande

Neutrino Experimental Facility





岐阜県神岡町地下1000m

50000トン水チェレンコフ

20インチPMT約12000本

1996〜

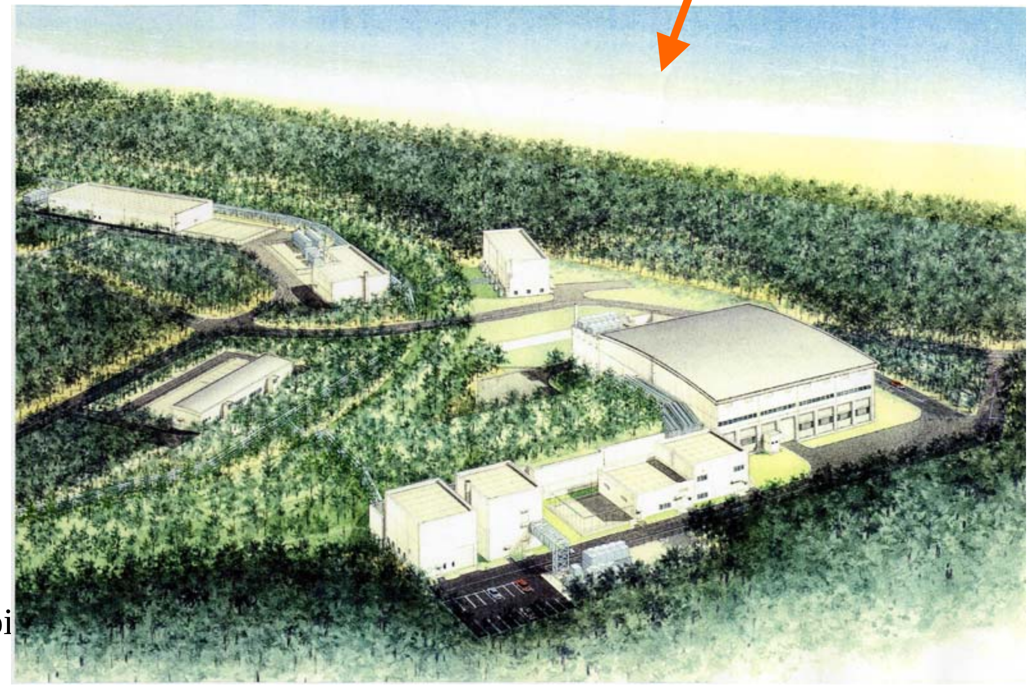
taken from
S. Nagamiya

Hadron Experimental Facility

Number of Users: about 600

(about 1/3 from Japan)

taken from
S. Nagamiya



Upgrade Plans for 50 GeV

- Power beyond 1 MW (neutrinos to study CP violation in the leptonic sector)
  - Design study was advanced to 1.3 MW.
  - Possibility up to 2.7 MW is in progress by the Accelerator group.
  - Users want up to 4 MW.
- Muon Storage Ring (LFV, muon g-2, etc.)
  - Need additional extraction beam line.
  - Exit was already prepared.
  - Anti-protons together with muons?
- Polarized Protons
  - Study group was formed.
  - Installation of Siberian snakes seems possible.
- Heavy Ion Acceleration
  - Interest exists among users.
  - Need technical studies.

Brookhaven involved

taken from
S. Nagamiya

further details:

http://jkj.tokai.jaeri.go.jp

Outline

- **motivation**: "the quest for pdfs at large x"
- **theor. framework (I):** pQCD & hard scattering
- **expectations**: pion and photon production @ J-PARC
- **theor. framework (II)**: resummations
- **concluding remarks**

I. Motivation

“the quest for pdfs at large-x”

“counting rules”: do they count?

interest in $x \to 1$ behavior of pdfs started some time ago:

Farrar, Jackson; Close, Sivers; Blankenbecler, Brodsky; Brodsky, Gunion; Brodsky, Schmidt; ...

VOLUME 35, NUMBER 21 PHYSICAL REVIEW LETTERS 24 NOVEMBER 1975

Pion and Nucleon Structure Functions near $x = 1$*

Glennys R. Farrar† and Darrell R. Jackson
California Insitute of Technology, Pasadena, California 91125
(Received 4 August 1975)

In a colored-quark and vector-gluon model of hadrons we show that a quark carrying nearly all the momentum of a nucleon ($x \approx 1$) must have the same helicity as the nucleon; consequently $\nu W_2^n/\nu W_2^p \to \frac{3}{7}$ as $x \to 1$, not $\frac{2}{3}$ as might naively have been expected. Furthermore as $x \to 1$, $\nu W_2^\pi \sim (1-x)^2$ and $(\sigma_L/\sigma_T)^\pi \sim \mu^2 Q^{-2}(1-x)^{-2} + O(g^2)$; the resulting angular dependence for $e^+e^- \to h^\pm + X$ is consistent with present data and has a distinctive form which can be easily tested when better data are available.

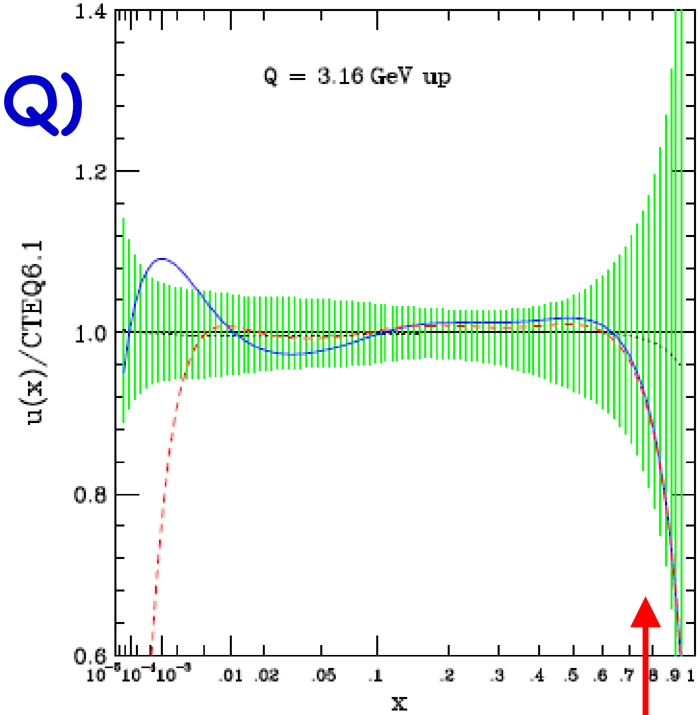
- precise exp. information for $x \to 1$ is still lacking
- rigorous pQCD framework just emerging (fact. theorem) Ji, Ma, Yuan; ...
- extraction of $x \to 1$ behavior complicated
  (presence of potentially large logarithms → resummations)

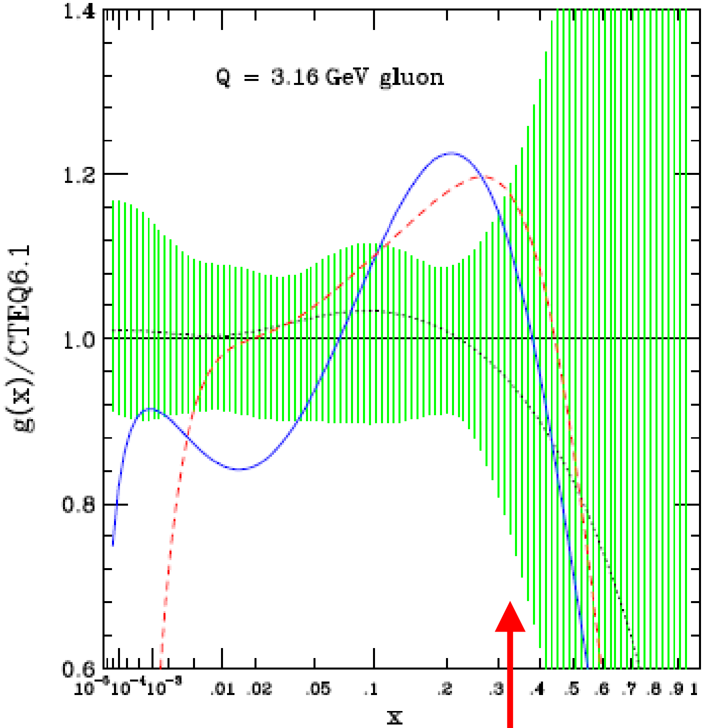
"counting rules": do they count?

latest global analysis results from CTEQ:

Huston, Pumplin, Stump, Tung

u(x,Q)





g(x,Q)

significant uncertainties for $x \gtrsim 0.75$

significant uncertainties for $x \gtrsim 0.3$

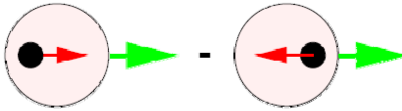
✓ fits always favor $u(x,Q) \sim (1-x)^{3 \div 4}$

$g(x,Q) \sim (1-x)^{0.8 \div 3.6}$ (best fit 1.7) ?

unstable w.r.t. fact. scheme, Q

"counting rules": do they count?

much less is known for helicity-dependent pdfs: $\Delta f(x) \equiv f_+^{N_+}(x) - f_-^{N_+}(x)$

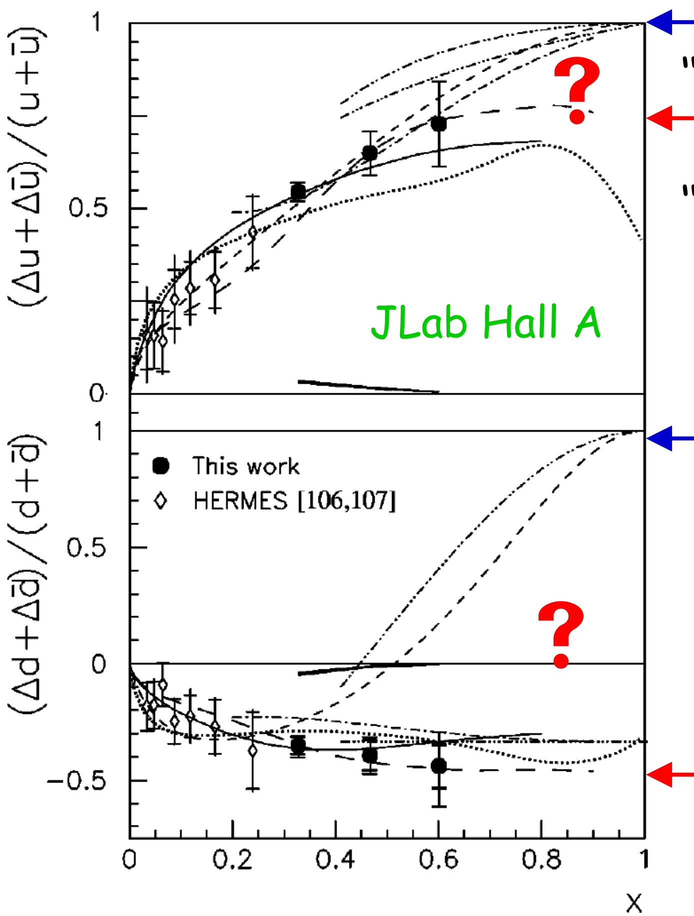


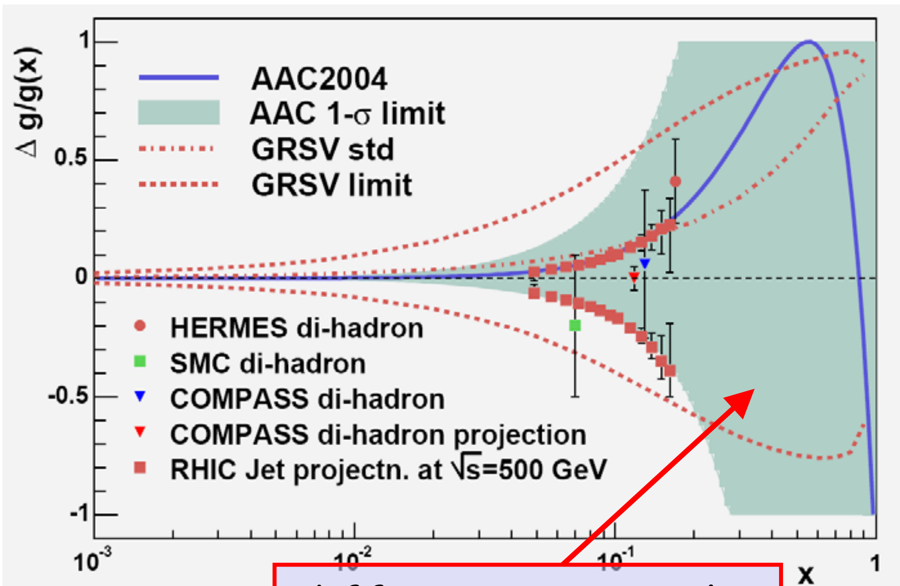
"helicity retention": $(\Delta f/f) \to 1$

Farrar, Jackson; Brodsky, Schmidt; Brodsky, Burkardt, Schmidt

"statist. parton model": $(\Delta u/u) \to 0.75$, $(\Delta d/d) \to -0.5$

Bourrely, Buccella, Soffer





diff. to access with present experiments

the big picture: impact on LHC physics

unpol. pdfs are vital for reliable predictions for new physics signals *and* their background cross sections at the LHC

high precision pdfs are crucial as they can compromise the potential for new physics discovery: Ferrag; ...

- high-x gluon uncertainty: reduces discovery reach in dijets
  5-10 TeV $\rightarrow$ 2-3 TeV
- high-x quark uncertainties: similar for Drell-Yan process

pdf uncertainty relevant for large Higgs masses, $Ht\bar{t}$ prod., ...
Djouadi, Ferrag; ...

ATLAS is looking into their pdf constraining potential

compelling reasons to check what can be done at a high-luminosity but low energy machine like J-PARC

we have to be prepared, however, for complications due to the low c.m.s. energy ...

II. Theoretical framework (i)

pQCD & hard scattering

the pQCD approach to hard scattering

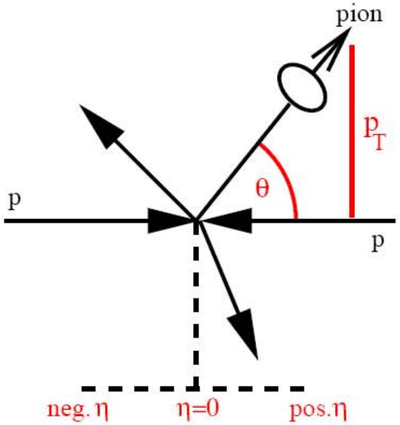
if hardness of probe is large enough ($\alpha_s(Q) \ll 1$), perturbative QCD can be used to make *quantitative predictions*
(exploiting asymptotic freedom of QCD)

Gross, Wilczek; Politzer 

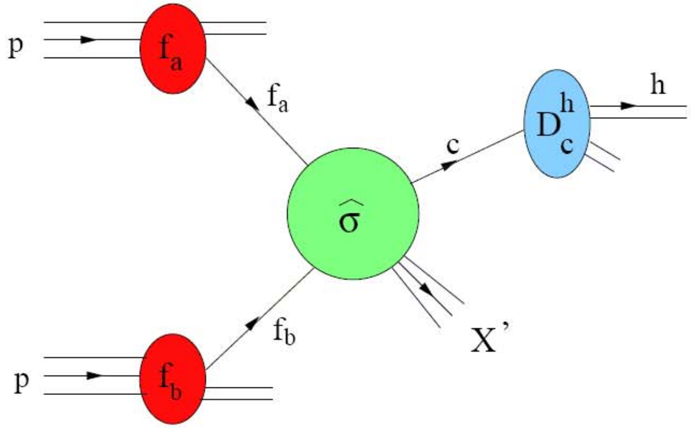
starting point: factorization theorem & universality of pdfs

Libby, Sterman; Ellis et al.; Amati et al.; Collins et al.; ...

example : (un)polarized inclusive high-p_T pion production



factorization $\longrightarrow$ theorem



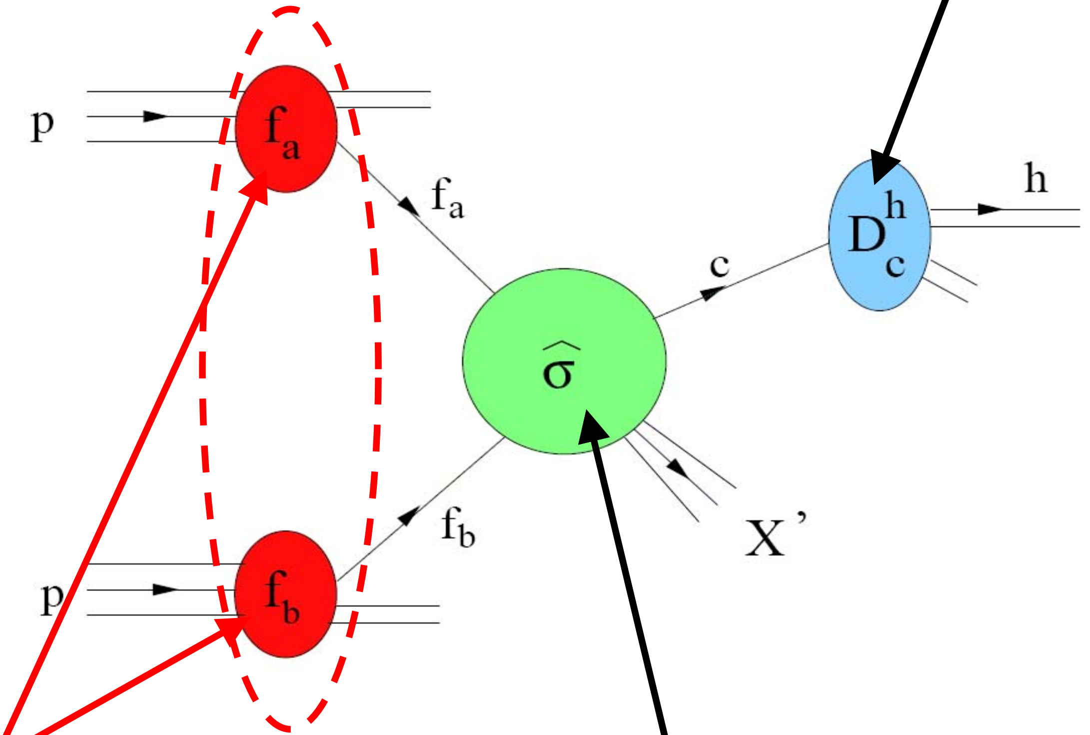
the pQCD approach to hard scattering

the strategy is simple …

extract from e^+e^- data

measure!

$d(\Delta)\sigma \simeq$



learn about
hadronic/spin structure

compute as a power series in α_s in pQCD

the pQCD approach to hard scattering

in more "mathematical" terms:

long-distance

from exp.; μ-dep.: $d\sigma/d\mu = 0$ (pQCD)

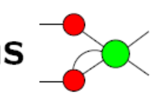
$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc} \int dx_a\, dx_b\, dz_c\, \Delta f_a(x_a, \mu_f)\, \Delta f_b(x_b, \mu_f)\, D_c^{\pi}(z_c, \mu'_f)$$

$$\times \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu'_f, \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

short-distance

calculable in pQCD: power series in α_s

power corrections



neglected

"features":

- separation between short- and long-dist. not unique (*fact. scheme*)
- theory calculation depends on *unphysical fact./renorm. scales*
- factorized "picture" good up to power corrections

the pQCD approach to hard scattering

the scale dependence is inherent to a pQCD calculation:

- a *measurable* cross section $d(\Delta)\sigma$ has to be *independent* of μ_r and μ_f

$$\frac{d(\Delta)\sigma}{d \ln \mu_{r,f}} = 0 \quad \longrightarrow$$

renormalization group eqs.
like DGLAP evolution

- if we truncate the series after the first N terms, there will be a residual scale dependence of order (N+1) $\longrightarrow$ theor. error

- there is no such thing like "the right scale" (not even Q in DIS!)

the harder we work, the less the final result should depend on these artificial scales

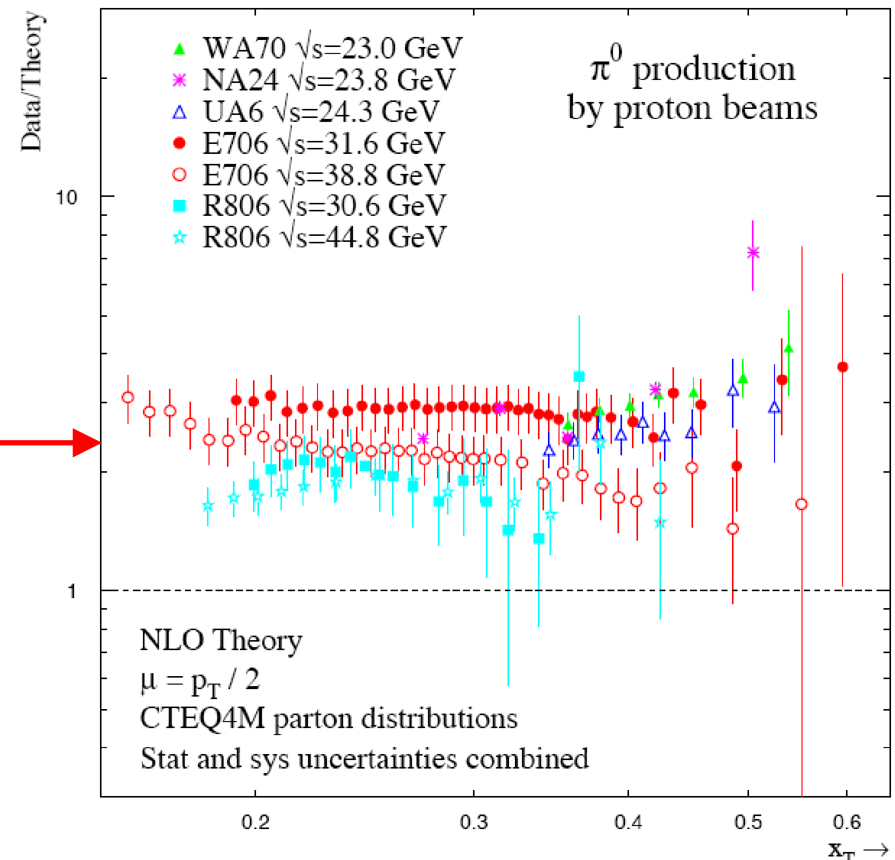
a powerful gauge of the reliability of a pQCD calculation

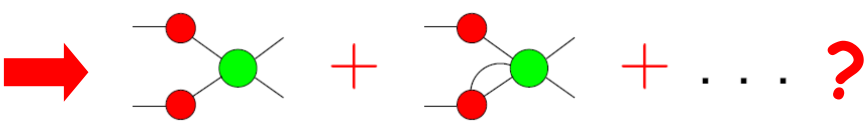
potential problems at fixed-target energies

key question: do we really talk about *hard* scattering if $\sqrt{S}$ is small ??

a priori we don't know, but

- in pp collisions, hardness is controlled by the observed transverse momentum: $p_T^{\max} = \sqrt{S}/[2\cosh(\eta)]$ small !!
- usually NLO pQCD undershoots data
  example: pion producion





not necessarily!

significant improvement after resummation of large logarithms to all orders (later in the talk)

Apanasevich et al.; Aurenche et al.; Bourrely, Soffer

III. Expectations

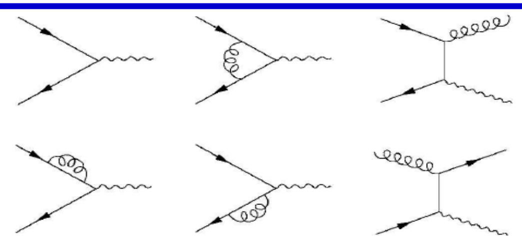
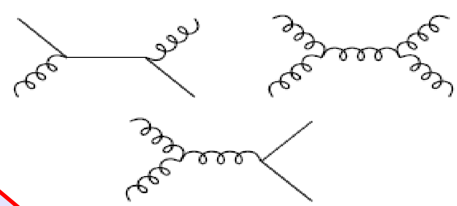
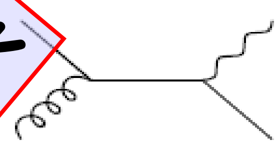
pion and photon production @ J-PARC

hard processes relevant at J-PARC energies

interesting hard probes: Drell-Yan lepton pairs, inclusive pions, and prompt photons

U: unpolarized
L: long. polarized
T: trans. polarized

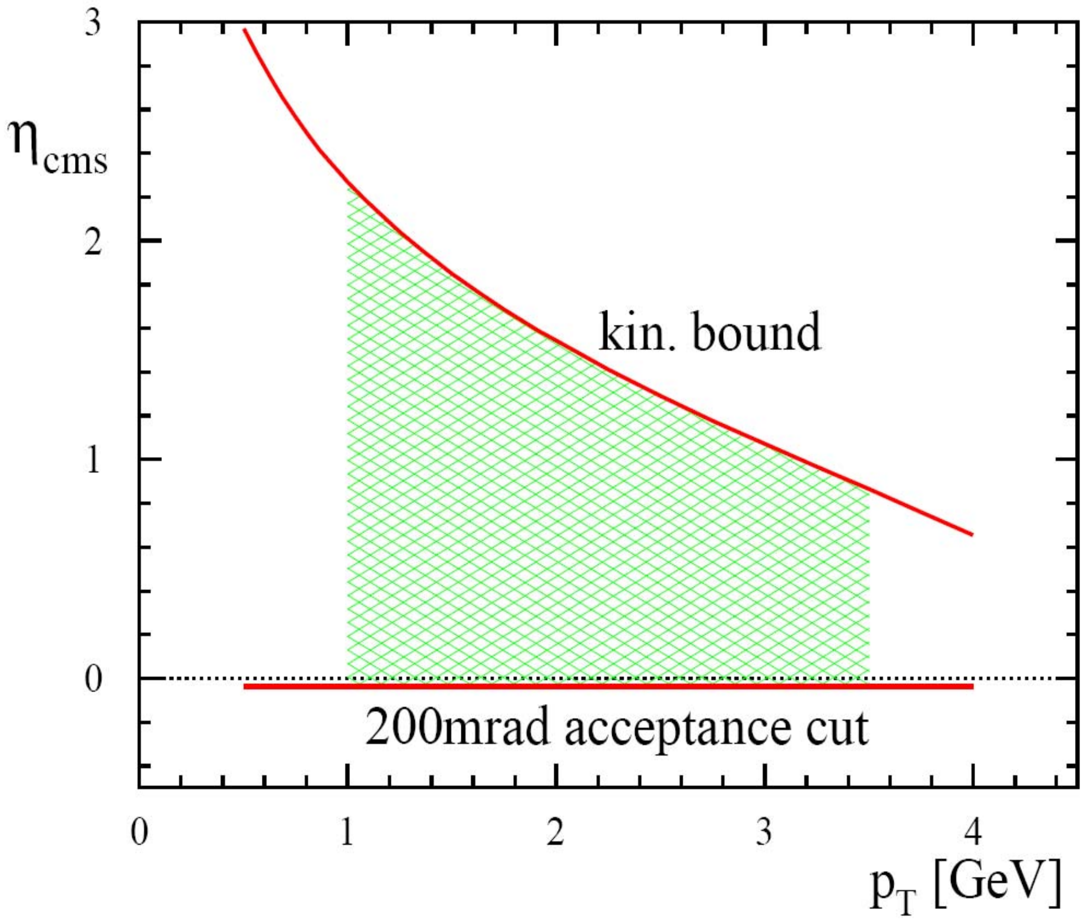
NLO QCD corrections to all reactions are known:

Drell-Yan		see talks by H. Yokoya & H. Kawamura
pions		Aversa et al. (U); de Florian (U,L); Jäger et al. (U,L); Mukherjee, MS, Vogelsang (T)
prompt photons		Aurenche et al. (U); Baer et al. (U,L); Contogouris et al. (U,L); Gordon, Vogelsang (U,L); Mukherjee, MS, Vogelsang (T)

THIS TALK

inputs to all pQCD calculations

50 GeV proton beam (polarization 75%) on fixed target
target polarization 75%; dilution factor 0.15; integr. luminosity: 10fb^{-1}



≈ COMPASS-like angular acceptance: 200mrad

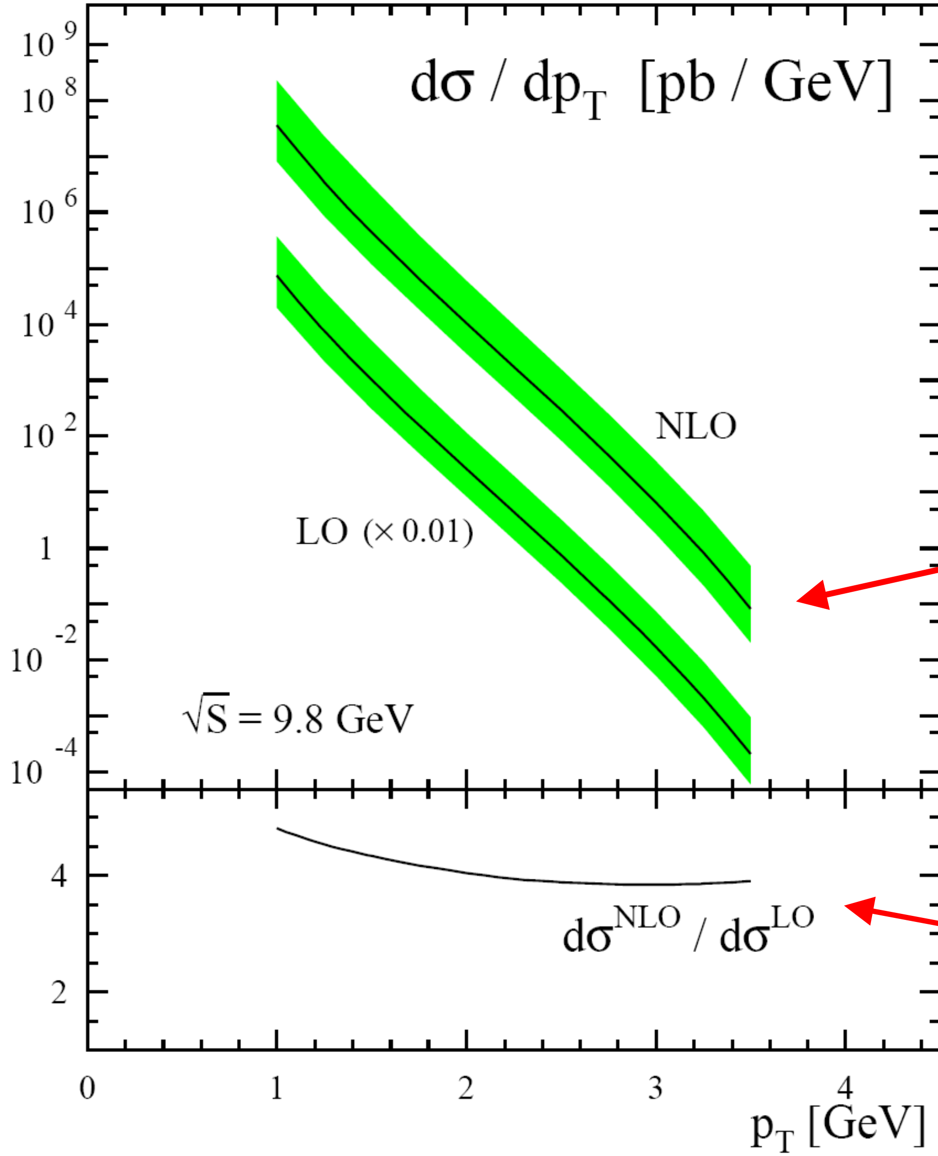
<u>choice of pdfs</u>:

- CTEQ6 (U)
- GRSV (L)
- "Soffer saturated" (T)

<u>choice of frag. fcts.</u>:

- KKP

single-inclusive pion production (unpolarized)

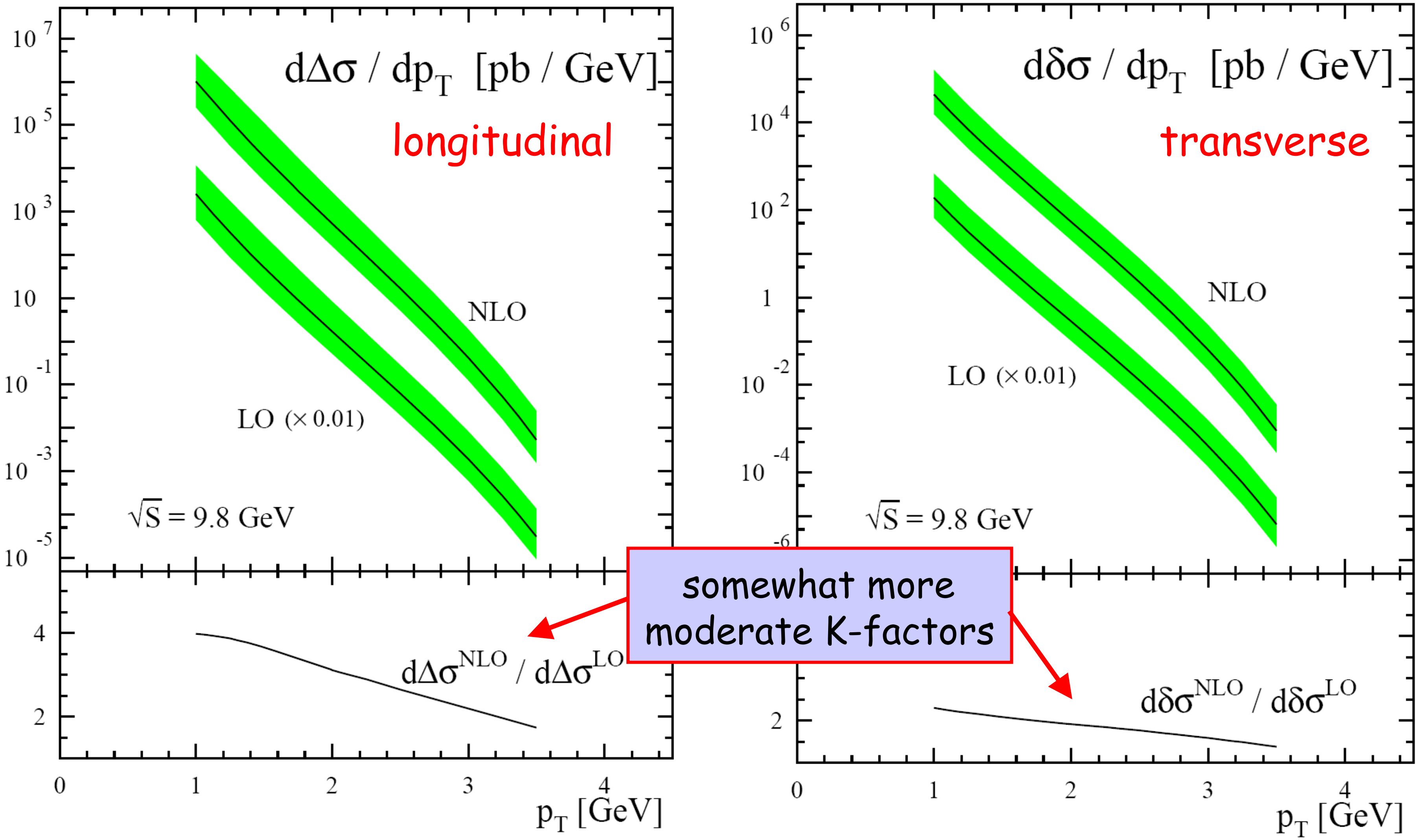


no improvement in scale uncertainty

scales used: $p_T \div 4p_T$

significant NLO corrections

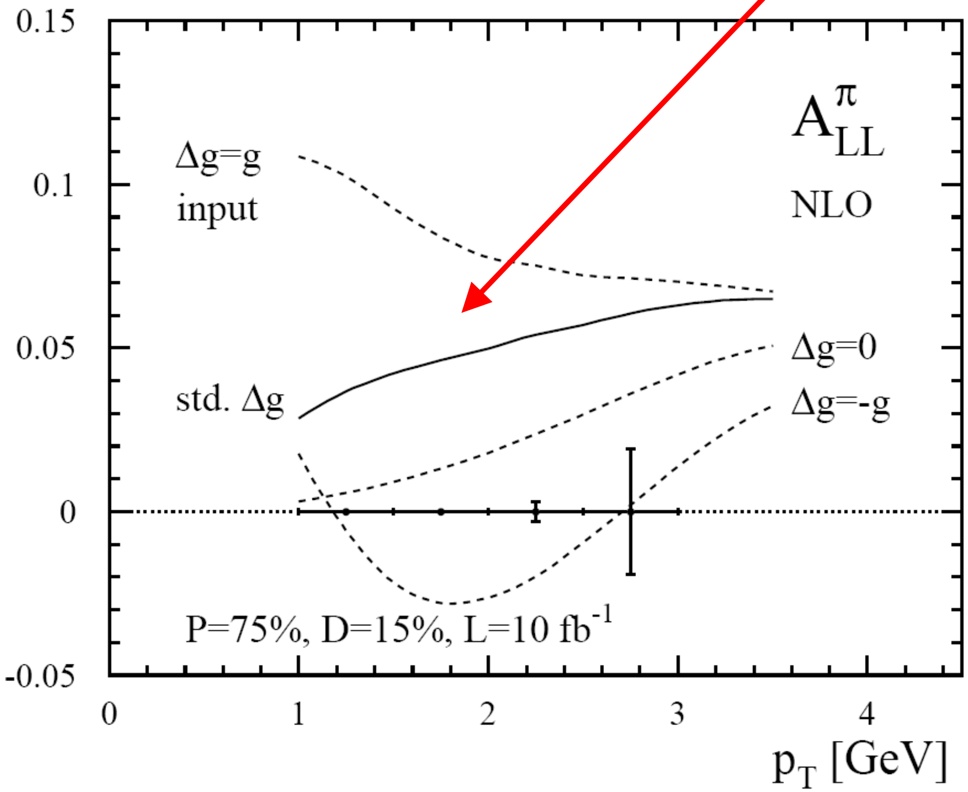
single-inclusive pion production (long./trans. pol.)

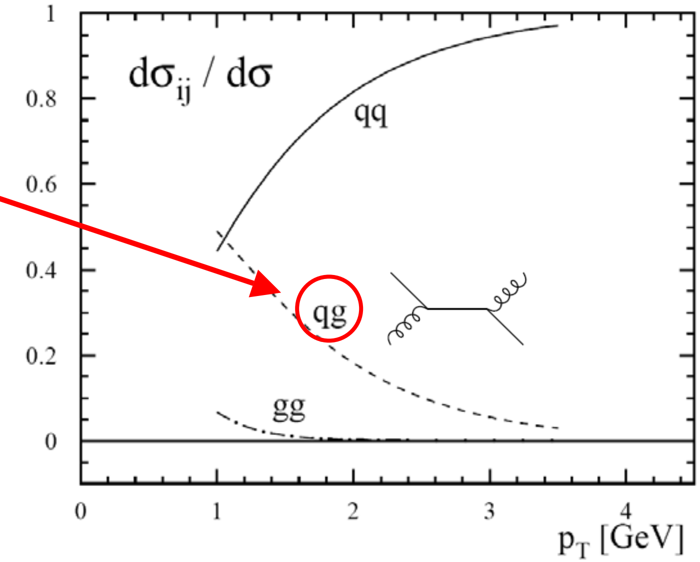


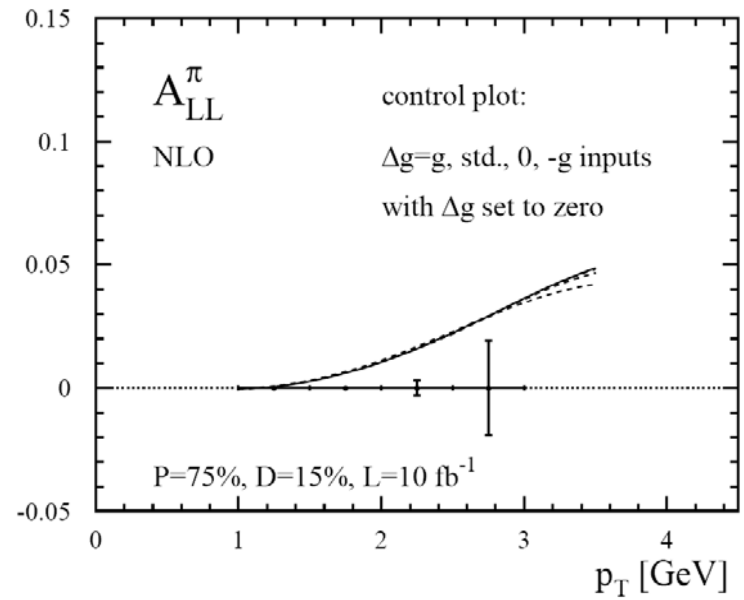
somewhat more moderate K-factors

single-inclusive pion production (A_{LL} & subproc.)

sensitivity to Δg through qg-scattering

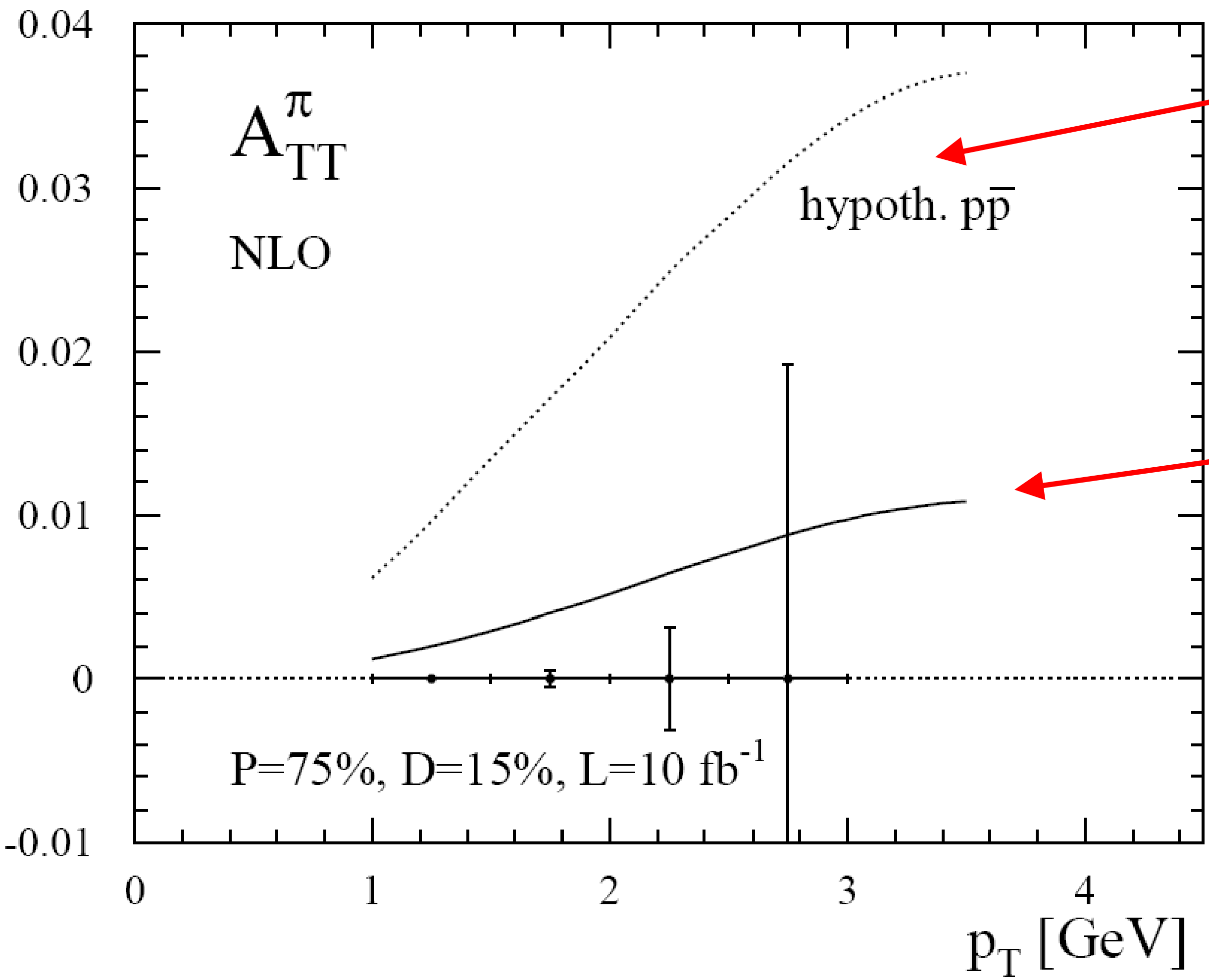






large x probed! 0.2 0.4 0.6 $\frac{2p_T}{\sqrt{S}}$

single-inclusive pion production (A_{TT})



$q\bar{q}$ proc. dominant

$\rightarrow p\bar{p} \gg pp$

upper bound for A_{TT}

"Soffer inequality"

$$2|\delta q| \leq q + \Delta q$$

saturated Soffer; Sivers

as expected:

$A_{TT} < A_{LL}$

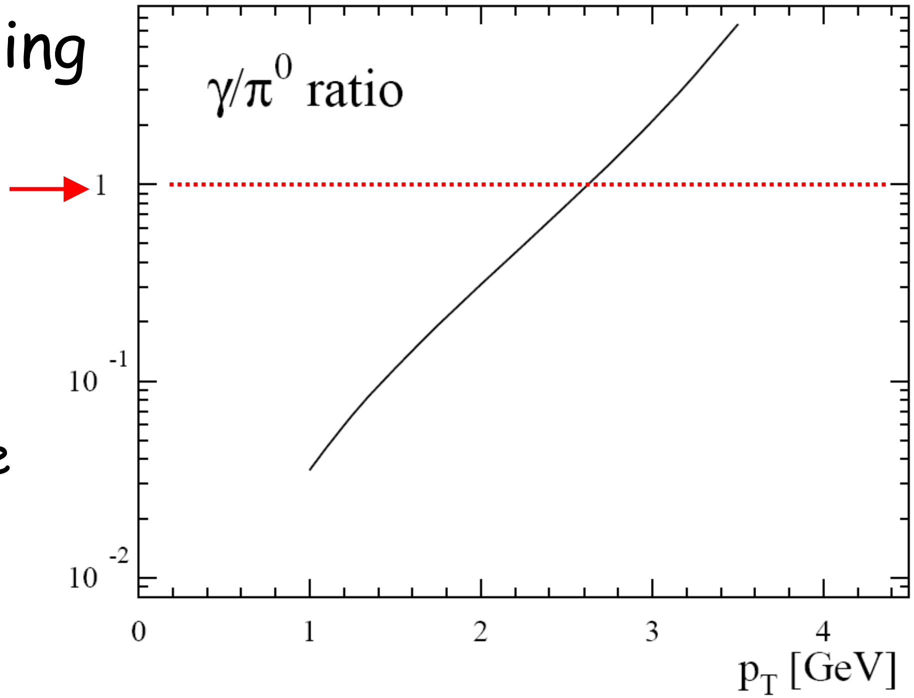
(lack of gluons)

Jaffe, Saito

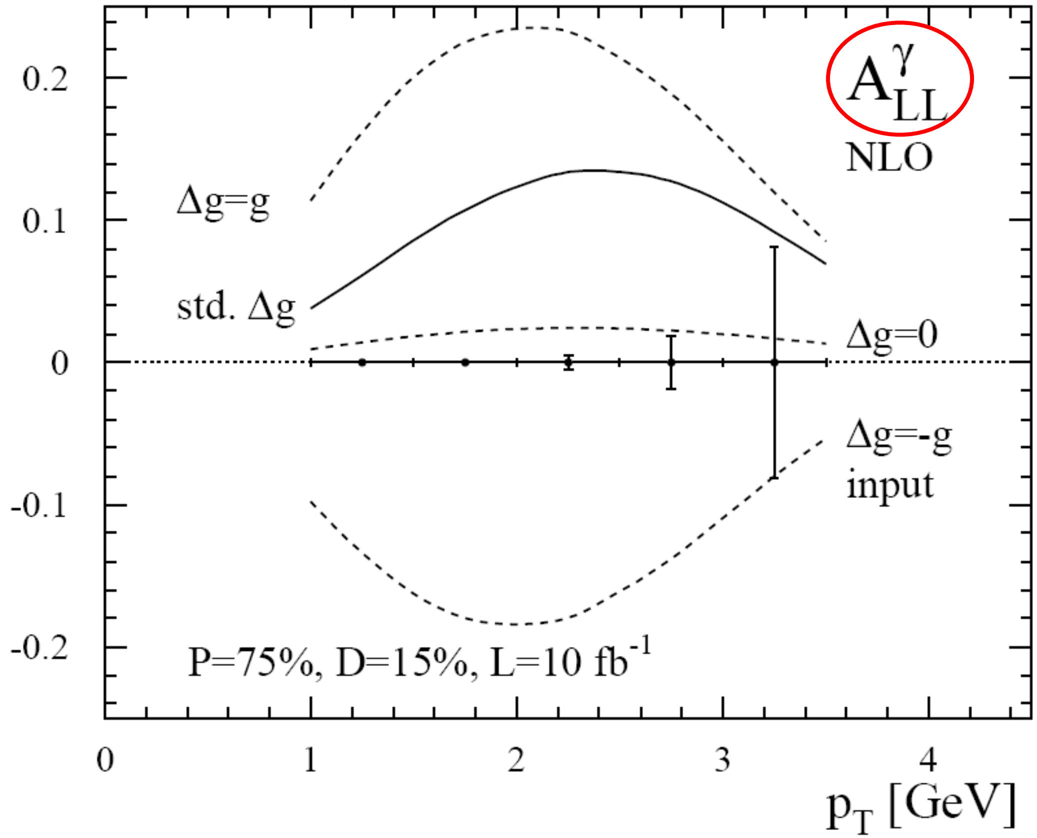
prompt photon production

- the scale dependence and K-factors are equally good/bad as for inclusive pion production ($\longrightarrow$ focus on A_{LL} & A_{TT})
- we adopt the isolation criterion of Frixione (no fragmentation contr.; R=0.4, ε=1)
- γ/π^0 ratio could be interesting to look at

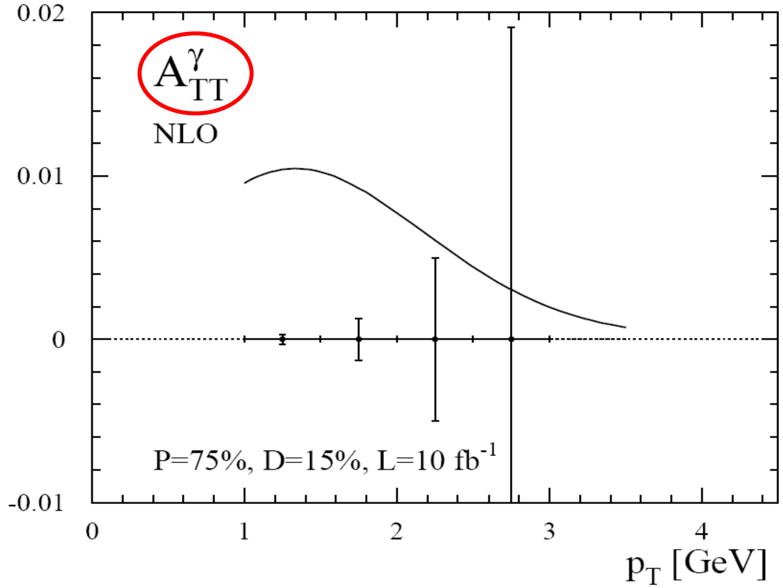
at RHIC we observe a strong rise but γ/π^0 is still less than one



prompt photon production (A_{LL} & A_{TT})



A_{TT}: again, this is an *upper* bound



A_{LL}: well-known sensitivity to Δg through $qg \to \gamma q$

independent of the polarization and the process we observe

- ✘ a large residual scale dependence also in NLO
- ✘ very sizable NLO corrections
- ✓ excellent prospects to constrain pdfs at large x

we should work harder to decide whether pQCD is at work or not

IV. Theoretical framework (ii)

resummations

resummations: general idea

fixed order pQCD has many successes but also failures

key question: why problems in fixed-target regime and
why near perfect at colliders ??

at partonic threshold:

$$\hat{x}_T = \frac{2p_T}{\sqrt{\hat{s}}} \to 1$$

- just enough energy to produce high-p_T parton
- "inhibited" gluon radiation

→ IR cancellation leaves large logarithms from soft gluons

as $\alpha_s^k \ln^{2k}(1-\hat{x}_T^2)$ at the k^{th} order:

$$p_T^3 \frac{d\hat{\sigma}_{ab}}{dp_T} = p_T^3 \frac{d\hat{\sigma}_{ab}^{\text{Born}}}{dp_T} \Big[1 + \underbrace{\mathcal{A}_1\, \alpha_s \ln^2\left(1-\hat{x}_T^2\right) + \mathcal{B}_1\, \alpha_s \ln\left(1-\hat{x}_T^2\right)}_{\text{NLO}}$$

$$+ \ldots + \mathcal{A}_k\, \alpha_s^k \ln^{2k}\left(1-\hat{x}_T^2\right) + \ldots \Big] + \ldots$$

resummations: general idea

resummation of these dominant contributions to the pert. series to all order has reached a high level of sophistication

Sterman; Catani, Trentadue; Laenen, Oderda, Sterman; Catani et al.; Sterman, Vogelsang; Kidonakis, Owens; ...

- worked out for most processes of interest at least to NLL
- well defined class of higher-order corrections
- often of much phenomenological relevance

resummation (=exponentiation !!) occurs when Mellin moments are taken:

$$\alpha_s^k \ln^{2k}(1-\hat{x}_T^2) \to \alpha_s^k \ln^{2k}(N)$$

$$\Rightarrow \quad \hat{\sigma}(N) \overset{L\equiv\ln(N)}{\propto} \exp\left[\sum_{k=1}^{\infty} \alpha_s^k L^k (a_k L + b_k) + \mathcal{O}(\alpha_s^{k+1} L^k)\right]$$

leading log (LL) $\alpha_s^k L^{2k}$ after expansion

resummations: general structure

(slide from a talk by W. Vogelsang)

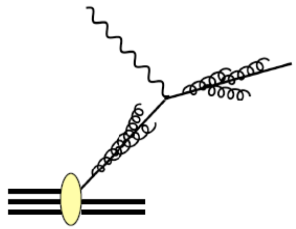
Fixed order

Resummation

LO	1				
NLO	$\alpha_s\, L^2$	$\alpha_s\, L$	α_s		$+\ \ldots$
NNLO	$\alpha_s^2\, L^4$	$\alpha_s^2\, L^3$	$\alpha_s^2\, L^2$	$\alpha_s^2\, L$	$+\ \ldots$
	$\alpha_s^3\, L^6$	$\alpha_s^3\, L^5$	$\alpha_s^3\, L^4$	$\alpha_s^3\, L^3$	$+\ \ldots$
	$\alpha_s^4\, L^8$	$\alpha_s^4\, L^7$	$\alpha_s^4\, L^6$	$\alpha_s^4\, L^5$	$+\ \ldots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
N^{k}LO	$\alpha_s^k\, L^{2k}$	$\alpha_s^k\, L^{2k-1}$	$\alpha_s^k\, L^{2k-2}$	$\alpha_s^k\, L^{2k-3}$	$+\ \ldots$
	LL	**NLL**	**NNLL**		

resummations: some LL exponents

DIS

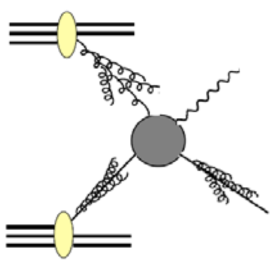


unobserved parton
Sudakov "suppression"

$$\exp\left[\frac{C_F\,\alpha_s}{\pi}\ln^2(N) - \frac{C_F\,\alpha_s}{\pi}\frac{1}{2}\ln^2(N)\right]$$

moderate enhancement

prompt photons

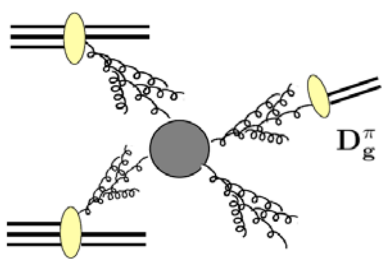


$q\bar{q} \to \gamma g$ $$\exp\left[\left(C_F + C_F - \frac{1}{2}C_A\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

$qg \to \gamma q$ $$\exp\left[\left(C_F + C_A - \frac{1}{2}C_F\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

exponents positive → enhancement

inclusive hadrons



e.g.

observed partons unobserved

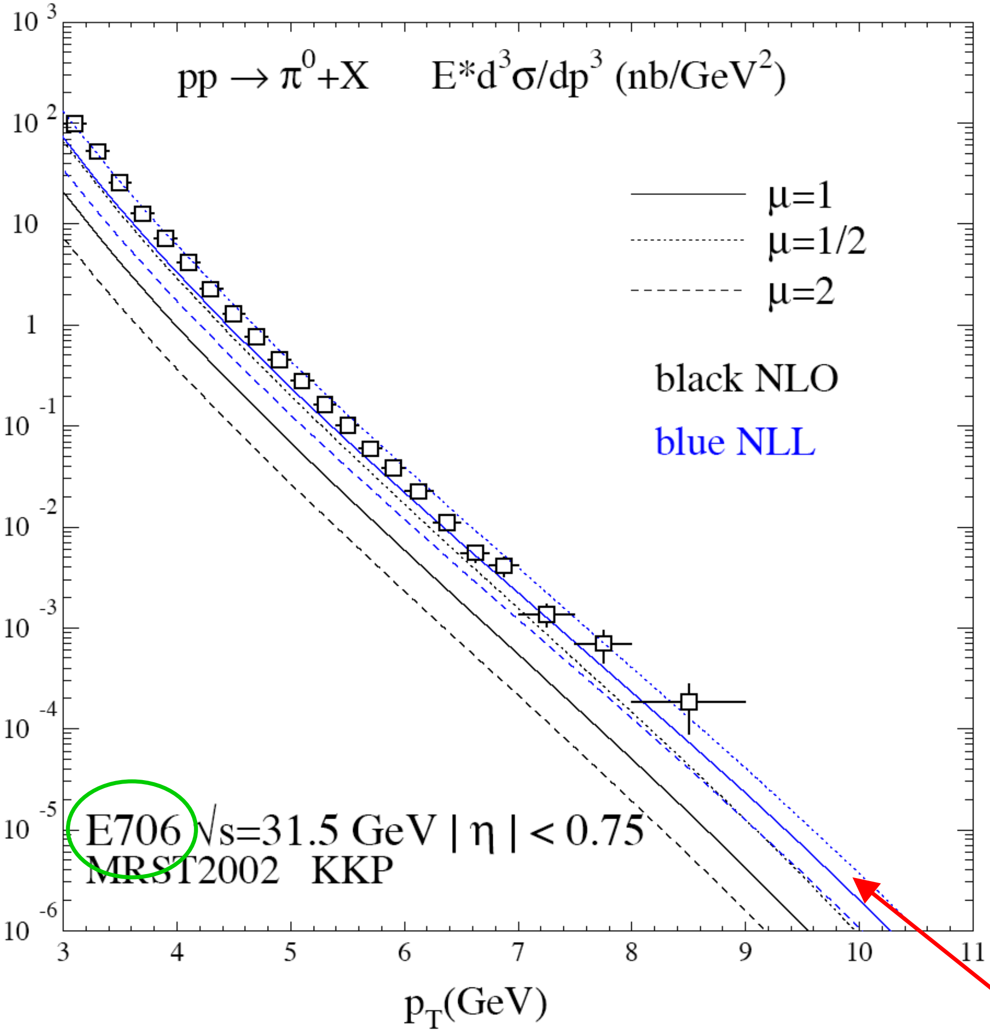
$gg \to gg$ $$\exp\left[\left(C_A + C_A + C_A - \frac{1}{2}C_A\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

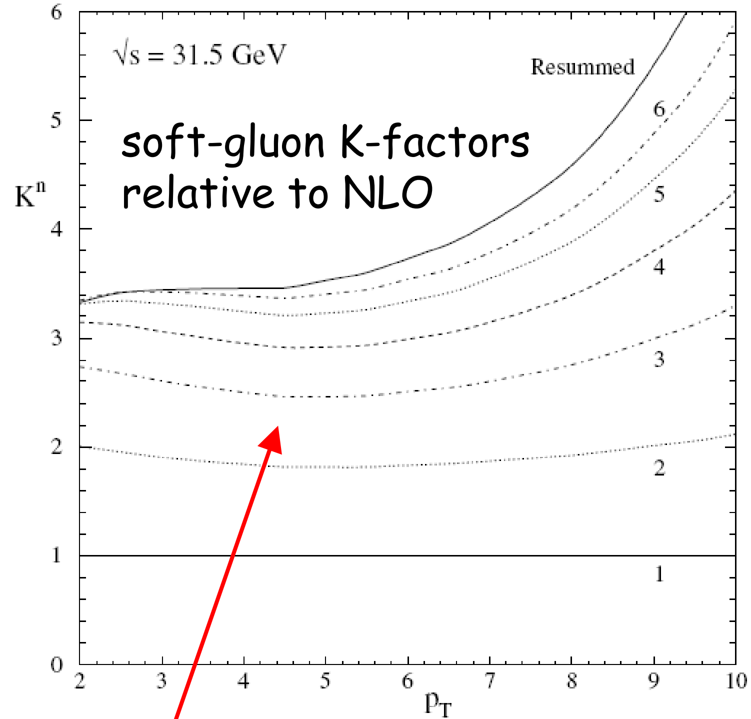
expect much larger enhancement

resummations: phenomenology

$pp \to \pi^0 X$

de Florian, Vogelsang





- very large enhancement in NLL
- good agreement with data now
- much reduced scale dependence

resummations: J-PARC (to-do list)

resummations seem to be mandatory at fixed-target energies

- ✓ technical framework available
- ✓ well-defined & systematic improvement of pQCD results
- ✓ much reduced uncertainties

bonus: resummations may provide information about power corrections through their sensitivity to strong-coupling regime Sterman, Vogelsang; ...

studies of power corrections/k_T effects prior to resummations do not make very much sense

to-do list: quantitative studies at J-PARC energies; expect:

- significant effects on cross sections
- partial cancellation of soft-gluon effects in A_{LL} in particular for prompt photons (simple color structure)
- reduction for A_{TT} (lack of gluons in $d\delta\sigma$)

V. Concluding remarks

scientific opportunities @ J-PARC

scientific opportunities @ J-PARC

two scenarios for hard scattering conceivable:

measurement of hard processes
(unpolarized first as benchmark)

compare with pQCD expectations
including resummations

it works

it does
not work

learn about
partonic & spin structure
at large x

learn about poorly understood
transition to the non-pert. regime
power corrections

coffee